2017-03

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http://hdl.handle.net/10945/58953

SYM-AM-17-076

Proceedings
of the
Fourteenth Annual Acquisition Research Symposium

Thursday Sessions
Volume II

Acquisition Research:
Creating Synergy for Informed Change

April 26–27, 2017

Published March 31, 2017

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

Acquisition Research Program
Graduate School of Business & Public Policy
Naval Postgraduate School

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Abstract

Set-based design (SBD) is a relatively new complex product development method. Its use has been well-researched in the automotive industry and to a lesser extent in other industries, and although it requires an upfront investment in resources, it has been shown to reduce design cycle-time, later stage re-work, and total ownership cost, and to improve design knowledge capture. Since 2005, the U.S. Navy has self-identified ship design as a process improvement priority and embarked in design tool and policy changes which resulted in the "Two Pass/Six Gate" process in 2008. Subsequent U.S. Navy ship design and acquisition actions have presented an opportunity to research and analyze the amenability of SBD, and its proposed benefits, with the U.S. Navy's Two Pass/Six Gate process to realize the efficiencies sought by acquisition executives. This study explored the application and benefits of using set-based design in acquisition programs. It identified specific changes to the existing Two Pass/Six Gate process in order to enable more widespread use of set-based design to improve the outcomes of complex acquisition programs.

Introduction

The 2005 National Shipbuilding Research Program (NSRP) Strategic Investment Plan (SIP) stated that ship design was the number one factor contributing to increased ship construction costs, and in 2007, the Commander of Naval Sea Systems Command (NAVSEA) was quoted as saying the U.S. Navy (USN) needs to re-establish its roots in terms of disciplined ship design (Keane, Firemann, et al., 2009; Sullivan, 2008). Since 2005, the USN has identified ship design processes and tools as the main problems leading to unaffordable ships.

The USN has explored using a product design approach known as Set-Based Design (SBD) or Set-Based Concurrent Engineering (SBCE). SBD, as a philosophy, has been utilized by Toyota Motor Corporation (TMC) to achieve acclaimed automobile manufacturing dominance. Ultimately, it aided TMC in producing better cars faster than its competitors. SBD has been shown to reduce product development cycle-time and has been touted as a contributing reason for TMC's dominance in the late 20th century (Ward et al., 1995). Further research of SBD use in other manufacturing industries has shown products designed via SBD result in reduced production cost (Raudberget, 2010). Producing better ships faster and cheaper is a process the USN desires to emulate by using SBD. Concurrent with sampling SBD, the USN has produced a suite of design tools to align with this new method of ship product development (Kassel, Cooper, & Mackenna, 2010).

This paper sets out to explore how this new approach to design and associated processes and tools might be utilized inside the SECNAV 5000 acquisition instructions and within the confines of the DoD/JCIDS/PPBE socio-technological system to realize efficiency gains in USN ship design and acquisition.

Different Approaches to Ship Product Development

SBD is contrasted with traditional or point-based design in a number of ways that are described in the following sections.

Point-Based Design (PBD)

The typical approach to design begins by defining a problem and then generating many alternative solutions (Chapman, Bahill, & Wymore, 1992). After some preliminary analysis, engineers select the alternative that appears to be the best, and then analyze, evaluate, and modify it until a satisfactory solution emerges (Ward et al., 1995). If all the initial alternative solutions could be graphed, engineers would know exactly which "point" in the design space they are analyzing, evaluating, and modifying. This approach of selecting a specific point in the design space and optimizing it is referred to as "point-based" design. However, with a point-based design, often as the fidelity of the analyses increases, design flaws begin to surface that require quick solutions to bring the design back into the feasible solution space. Often the design cannot be altered enough to achieve a feasible solution, at which point a new design alternative is chosen to re-start the design. The primary attribute of this approach is that a single solution is synthesized first, then analyzed and changed accordingly (Liker et al., 1996). A PBD process can be summarized by the following five steps (Bernstein, 1998; Liker et al., 1996):

1. Research the problem. During this step, designers inquire with the customer to clearly set problem requirements.
2. Once the requirements are known, engineers and designers use experience to quickly determine a large variety of potential solutions.
3. Engineers then perform preliminary analysis on all alternatives to determine a single, feasible, most opportunistic solution for further analysis.
4. The chosen concept is then analyzed and modified in detail to achieve all product requirements established in Step 1.
5. If the detailed design cannot be modified to meet all requirements, the process starts over at Step 1 or 2 until a solution is found.

Since the cost of correcting defects escalates as the design progresses, the PBD approach can result in poor results by performing the design process in a sequential-only method (Sobek, Ward, & Liker, 1999). The sequential process leads to incorrect work discovered late and challenges in integration. Delay of work is the main issue associated with the process, since major changes must be made once information is transferred to downstream activities (Ward et al., 1995).

Set-Based Design

The theoretical foundation for SBD was established in Allen Ward's MIT PhD thesis in 1989. His work presented a computer compiling program that would assist a mechanical engineer during the design of various systems. Bridging his research on mechanical systems to the broader context of all product development, Ward proposed two product development fundamentals (Ward, 1989):

1. All products should be designed with all viable options in mind.
2. Options should not be eliminated unless there is a logical reason to do so.

Ward's approach results in a gradual narrowing of the system solution space while investigating different design concepts in parallel. Keeping all feasible options in consideration for as long as possible was accomplished by considering groups of mechanical components as "sets," thus leading to the term "Set-Based Design."

In 1995, Ward et al. described a Second Paradox to how TMC executes its business, which included the following generalities: delaying decisions, communicating ambiguously with its suppliers, and pursuing an excessive number of prototypes. This Second Paradox formed the basis for what Ward's research group defined as a culture of SBCE, in which they were able to explain the paradox between seemingly inefficient sub-steps and the efficient overall process by summarizing the SBCE progress into four steps (Ward et al., 1995):

1. The design team considers "sets" of system solutions by defining options of possible sub-system solutions.
2. Possible subsystem design solutions are explored in parallel using analysis, expertise, and experiments.
3. The design team uses the analysis of each subsystem to gradually narrow the sets of system solutions that are possible.
4. Once the design team has found a preferred sub-system solution, the design does not deviate unless absolutely necessary.

Recently, Ghosh and Seering reviewed the previous 20 years of publications relating to SBD principles and characteristics. They qualitatively surmised that organizations performing set-based product development display two principles (Ghosh & Seering, 2014):

1. Considering sets of distinct alternatives concurrently.
2. Delaying convergent decision-making.

How SBD is executed is a unique process. At the beginning of SBD, the conceptual design is organized into separate sub-spaces along the lines of product form or function that align with individual expertise within the design team (Gray, 2011). During this decomposition phase, design teams establish design variables that represent interfaces between sub-spaces. Design teams identify ranges, or sets, for the interfacial design variables based on experts' opinions of what is possible. With interfaces defined that provide a range of possible sub-systems solutions, sub-space design teams are able to independently and concurrently create their own sub-system designs (Sobek et al., 1999).

During this stage of initial design, enough analysis is performed on sub-systems to identify priority sub-system solutions. After preliminary analysis, design teams meet and review sub-space design solutions to identify solutions that have overlapping (shared) design variable ranges. The overlapping regions represent a design space that is feasible for all sub-space design teams (Bernstein, 1998). During these meetings, design teams communicate their preferences for the originally established design variables. Given preferences of other sub-space design teams, the design groups then re-convene and rework designs to incorporate trade-offs and benefits for overlapping feasible design regions. The entire process is gradually repeated with higher fidelity analysis. This process results in eliminating, or not further investigating, regions of the overall design space that are sub-optimal to the whole group (Ward et al., 1995).

An organization that displays both principles can be labeled as utilizing set-based product development. Tailoring the principles to a process for larger complex systems like ship design and acquisition, we offer the following as general principles of SBD:

Principle 1: Establish the design space and sub-divide along areas of expertise: concurrent subsystem evaluation

Principle 2: Gradually and deliberately reduce the design space by integrating preferred subspaces: discovery by elimination

The main benefit of SBD is that it forces teams of designers to communicate in an effective and efficient manner along the lines of product architecture and interfaces—performing design using Principles 1 and 2. SBD communication enacts a decision-making process that enables effective and logical decisions to be made with confidence. Fundamentally, SBD is a design method that discovers the optimal solution by a gradual elimination of the design trade space. The potential benefits of SBD can be summarized as the follows:

- Reduction of later stage rework when the cost of change is more expensive; therefore, less costly to design, build, and maintain the product
- Reduction of design cycle-time; therefore, less costly to design the product and more market share gained from entering an opportunity market sooner
- Better design knowledge capture; therefore, less costly to incorporate customer changes during design or to perform future similar product designs
- A better solution is found because of the methodic reduction of the design trade space; therefore, higher customer satisfaction

Traditional Ship Design

Figure 1 presents a ship design example for a surface cargo ship. This ship design spiral has been ship design tradition since originally presented in 1959 by J. H. Evans.

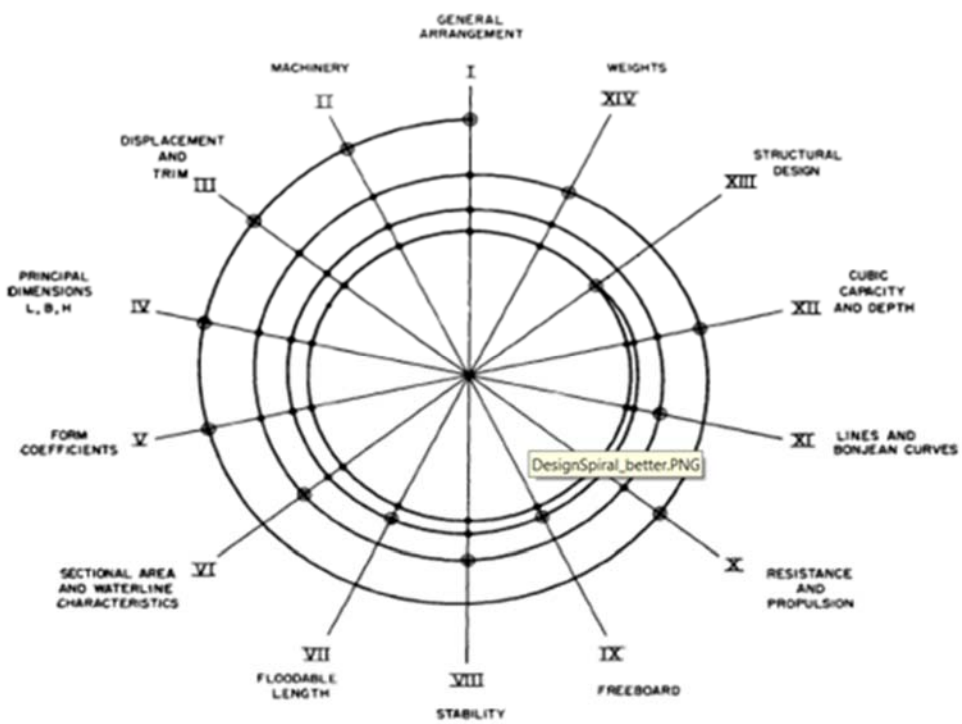

Figure 1. Ship Design Spiral
(Evans, 1959)

This model recognizes the complex nature of the ship design and approaches the design process from the view of conducting iterative passes from one element to the next: weight, volume, stability, resistance, powering, strength, and so on. Systematically addressing each element in sequence, and doing so in increasing detail in each pass around the spiral can reach a single balanced design that satisfies all constraints (Frye, 2010). The model incorporates most of the product development process for ships. Iterations around the spiral would first be performed at the concept design level and gradually proceed toward detailed production design. What aren't captured in Evans's model are the operations and support phases of ship product development.

This approach to ship product development is synonymous with the term *point-based design* since each pass through the spiral attempts to resolve conflicts between elements and develop a design that meets requirements.

Research Methods

Information for this study was gathered by conducting research of open source literature and unclassified databases. Databases accessed were contained on website servers for the Defense Acquisition Management Information Retrieval (DAMIR), Assistant Secretary of the Navy Research, Development, and Acquisition Information System (RDAIS), and USN Visibility and Management of Operating and Support Costs (VAMOSC) systems. In some cases, program-specific documents were classified as Unclassified/For Official Use Only or releasable to only DoD employees or contractors. These documents were only used to identify potential candidates for interviews and are not referenced or cited in this work.

Research data was also obtained through interviews with various stakeholders, decision-makers, sponsors, managers, and engineers within the DoD and Department of the Navy (DoN). Twenty-one interviews were conducted in support of this work from individuals in ASN RDA, OPNAV, CAPE, NAVSEA 05, NSWC-CD, PEOSHIPS, PEOSUBS, CSRA/DoN contractor, and SSGC. Interviewees were asked general questions to understand what the USN values and when in the ship design and acquisition process. More specific questions were then asked to understand processes and tools used to perform respective parts of ship design and acquisition processes.

Case Studies of SBD in the USN

The USN has recently experimented with the use of SBD in acquisition programs. The following examples are programs that actively tried to apply principles of SBD. They are the Pre-PD on Ship to Shore Connector (SCC), Pre-Analysis of Alternatives (AoA) design for the Amphibious Combat Vehicle (ACV), and Pre-AoA design by the Small Surface Combatant Task Force (SSCTF). In each case, some of the author's principles of SBD were identified and some proposed benefits of SBD were achieved.

Ship to Shore Connector (SSC)

The SSC program was created to produce a replacement for the Landing Craft Air Cushioned (LCAC) amphibious transport vehicle. LCACs were designed in the late 1970s and produced during 1984 through 2000. LCACs are still in service today with the oldest LCACs expected to begin retirement in 2019. When considering options for maintaining LCAC amphibious landing capability, the USN performed Exploratory and Pre-AoA design studies in 2006 that resulted in an approved Initial Capabilities Document (ICD) and AoA in 2006 and 2007, respectively (Mebane et al., 2011).

Like other USN ship AoAs, the preferred AoA variant did provide enough detail to satisfy producing the Capabilities Development Document (CDD; Singer, Doerry, & Buckley, 2009). Thus, Pre-Preliminary Design was performed to support refining the draft CDD. NAVSEA ship design leadership decided to pioneer using SBD on the LCAC replacement in accordance with in-progress design process improvement initiatives. These early studies established the LCAC replacement as the SCC program under PMS-377 with a Ship Design Manager (SDM) from NAVSEA 05D. USN leadership was aware of the proposed benefits of SBD, but OPNAV and PMS-377 were most interested in SBD's advantage of critical design decision knowledge capture (McKenney & Singer, 2014) because of the expected high military leadership turnover during typical USN ship design and acquisition (Mebane et al., 2011).

How SBD on SSC Was Executed

Without a formal process described in any USN instruction for SBD, the SCC project team utilized the Decision Object System Engineering (DOSE) method to guide their process for decision-making with the support of experienced academics and consultants familiar with SBD. DOSE's use of knowledge-mapping techniques facilitated team decision-making along lines of functional expertise (Buckley & Stammnitz, 2004; CDI Marine, 2009). With a method to guide overall design execution, the SDM assembled and partitioned the SSC design team per Figure 2 and structured the execution of SSC SBD in three generic phases: (1) Trade space setup and Characterization, (2) Trade space reduction, and (3) Integration and Scoring (Mebane et al., 2011).

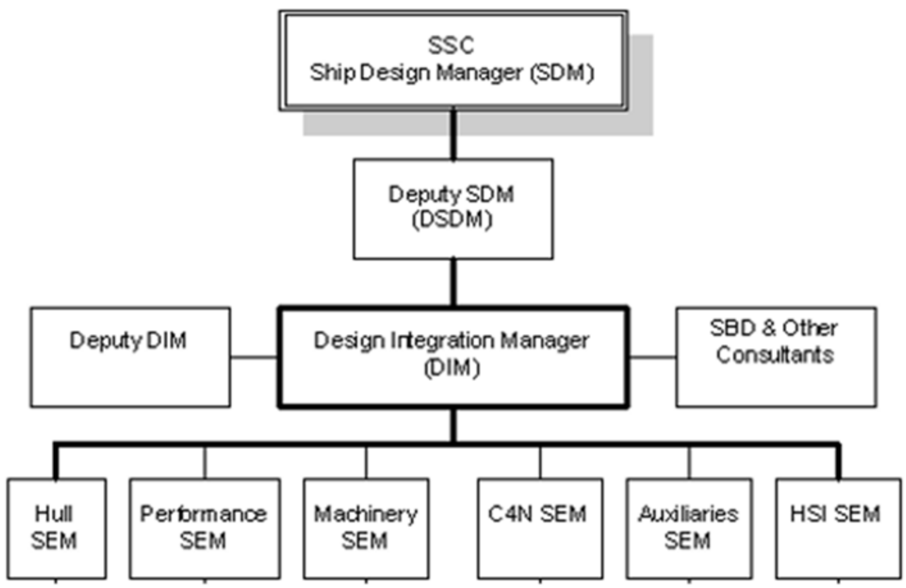

Figure 2. SSC Design Team Structure
(CDI Marine, 2009)

- Ship Design Manager (SDM): The lead system engineer on the project. This individual represents the design team in all matters with outside organizations.
- Design Integration Manager (DIM): This individual is responsible for facilitating communication, decision-making, and integration among all the elements.
- System Engineering Manager (SEM): These individuals represent the system expert in the specific element field.

Trade Space Setup and Characterization

The inputs used for the design effort were shaped into what the design team referred to as a craft-level Functional Design Document (FDD), which was a compilation of NAVSEA executive guidance, the SSC Analysis of Alternatives (AoA) and the SSC Initial Capabilities Document (ICD), and Landing Craft Air Cushion (LCAC) Service Life Extension Program (SLEP) requirements and lessons learned. Using the performance attributes identified in the FDD, Air cushion vehicle Design Synthesis Model (ADSM[1]) was used to convert overall craft performance into performance ranges for each Element: Hull, Machinery, Performance, Combat/Command/Control & Communication Networks (C4N), Auxiliaries, and Human System Integration (HSI). These Element performance ranges were converted into Functional Requirements Documents (FRDs) to guide Element trade space characterization and analysis. When characterizing their trade spaces, SEMs were given latitude to explore any potential solution as long as they had concurrence from a Technical Warrant Holder (TWH) that the proposed system solution was acceptable. At the end of Element characterization, the SEM had a Trade Space Summary (TSS), in the form of an MS Excel spreadsheet, which captured TWH comments, approvals, and future trade space reduction decisions.

Trade Space Reduction

After establishing Element solution trade space acceptability, SEMs used design of experiments, or other analysis, to analyze their intra-element set of solutions for key design parameter preference or dominance. Model Based System Engineering techniques compared intra-element solutions against each other by identifying performance measures, modeling and simulation scenarios appropriate for each element based on Subject Matter Expert (SME) opinion. Some SEMs used Response Surface Methodology to compare alternatives, where others used a less rigorous approach because of the lack of design variable continuity over the FRD. This process was completely concurrent for each SEM and was supervised and facilitated by periodic Design Integration Team (DIT[2]) meetings. TSSs captured these reduction decisions. At the end of the trade space reduction phase, each SEM had a set of non-dominated intra-element solutions. These solutions were approved by TWH's as technically acceptable and concurred upon by the DIT as viable. The next step in the SBD design effort was to combine all Element solutions into craft variants.

Integration and Scoring

Towards the end of Trade Space Reduction, the DIT identified what they referred to as "negotiating relationships" between Elements, which resulted when the selection of one option in an Element influenced which options could work in the other Elements. Eliminating exclusions based on negotiating relationships resulted in the set of all potentially viable SSC crafts. Next, all potentially viable craft designs were submitted to a Balancing Process in which a design synthesis tool, similar to ADSM, was performed for each candidate craft to ensure design candidates pass a first order test for platform viability. For the SSC project, the balance process screened candidates for important high-level craft attributes: an initial stability check, a test for adequate power to get over the generated bow wave, and a test for

[1] ADSM is an air-cushioned craft-specific design tool created by TMLS and maintained by the USN for LCAC/SCC design
[2] The DIT consisted of the DIM, the Deputy DIM, and SBD consultants.

adequate power to maintain the required cruise speed. The balancing process eliminated another significant portion of SSC alternatives and produced a set of metrics for each variant that could be used for quantitative comparison. A scoring scheme using an Overall Measure of Effectiveness (OMOE) from multi-attribute utility was created to evaluate the remaining SSC variants between cost, risk, and performance. This resulted in a small group of high scoring variants in which the design team chose two variants, which only differed by hull material selection, to carry into Preliminary Design. Figure 3 captures the three phases of the SSC design process.

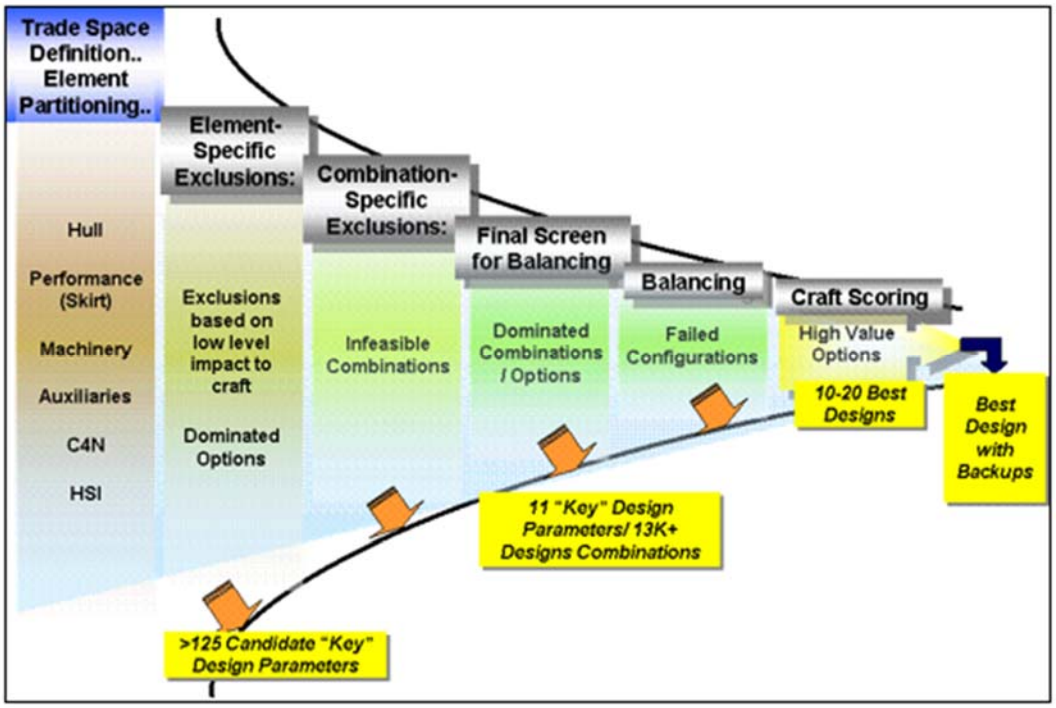

Figure 3. SSC Set Reduction Process
(CDI Marine, 2009)

Results of SCC SBD

At the end of design, two preferred, similar variants were identified by the team as the believed global optimums (Mebane et al., 2011; Singer et al., 2009). Additionally, a vast amount of design knowledge had been captured using the TSSs, specifically the negotiating relationships. The two SSC variants were generated by a process that evaluated functional specific trade spaces concurrently and reduced the trade space by eliminating dominated or infeasible options; thus, satisfying the authors' principles for SBD execution.

Programmatically, the SSC design was completed on time, within 10% of budget, and used little to no design margins (Doerry, 2010). Overall, in 2008, the SBD results for SSC were immediately used for Preliminary Design (PD), Contract Design (CD) and Gates 4/5 of the newly instituted two pass/six gate (2P/6G) process. The SSC program has proceeded past MS B and is supervising construction of the SSC test craft at Textron Marine and Land Systems.

Other Benefits of Using SBD in the SSC Program

Although the overall process used by the SSC team may not have been textbook SBD (McKenney & Singer, 2014), the USN was writing the textbook for using SBD during

SSC design efforts (Singer et al., 2009). The biggest lesson learned from the SSC Pre-PD design phase was that SBD principles could be translated into a process for use on USN ships/crafts. The SBD process not only quickly (within four months) produced results, but also the formal decision-making exclusions and eliminations provided excellent design knowledge capture. For SSC, knowledge capture was obtained by TSSs and the eventual discovery of negotiating relationships between functional Element groups. This design knowledge capture also led to a more fluid design review process during PD, CD, Gate 5, and MS B. The design team was able to immediately answer, or in even some cases prevent, design reviewer and higher level decision-maker questions about the recommended edges of the SCC design. Once design reviewers and higher level decision-makers understood the trade space elimination process, they became satisfied that an ideal solution had been reached. Thus, there was no need to further question why the design team arrived at their recommended solution. In the end, future fluidity of design review is what the USN hopes to achieve by capturing lessons learned from the SSC.

Design fluidity, in the SSC case, could be translated into better cost and schedule performance. By preventing the extra questions from reviewers during the PD, CD, and Gate 5 review phases, the SSC design team ultimately prevented undertaking additional studies to answer posed questions. In the past, these extra questions were considered to be significant due to either the seniority level that asked the question or because the question was generated in front of a large diverse group. After performing the study to answer the extra question, the conclusion often ended up being low value re-work.

Amphibious Combat Vehicle (ACV)

Another opportunity arose for a rapid ship/craft design learning event shortly after the SSC team finished their critical design review. In 2011, the United States Marine Corp (USMC) canceled the 40-year old Amphibious Assault Vehicle (AAV) replacement program, the Expeditionary Fighting Vehicle (EFV), due to poor reliability and excessive cost (O'Rourke, 2016a). The USMC immediately began re-planning for the development of a more affordable and sustainable amphibious combat vehicle (ACV). This resulted in an ICD to align capabilities and future CONOPs and an AoA that re-enforced the need for a self-deploying survivable craft. But neither the ICD nor AoA explored the operational benefits of a high water speed (HWS) craft (Burrow et al., 2013). With extra scrutiny on the ACV program from the previous EFV cancellation, senior USMC leaders expressed concern with proceeding with a low water speed craft without evaluating the HWS requirement, citing operational flexibility and the potential tactical advantage HWS might have (Burrow et al., 2013). To satisfy the "what about…/what's not shown on the slide" question from USMC leadership, the Assistant Commandant of the Marine Corps and ASN RDA developed an ACV directorate team to evaluate the cost and capability trade-offs of a HWS ACV.

The ACV design team was focused on expeditiously answering the "what about …" question while simultaneously using previous EFV information and capturing ACV design knowledge. The proposed reduced cycle-time and knowledge-capture benefits of SBD aligned with the ACV directorate's priorities. Therefore, the ACV design team desired to explore incorporating aspects of SBD, where possible, in the ACV design approach. In the end, the results of the ACV design produced a detailed cost–benefit assessment of the HWS requirement. Additionally, USN and USMC leadership became more aware of configuration diversity terminology and how early stage design decision information may be presented using a SBD approach.

How the ACV Design Was Executed

To assess the feasibility and cost of the HWS ACV, the ACV directorate established a design team, formulated an analysis plan, and executed a series of four focused design studies. Where possible, concurrent design efforts were performed, and design knowledge was shared between core teams to improve the validity and value of sequential ACV design studies.

With clear performance requirements, the ACV team generated a library of ACV components that could comprise an ACV variant based on the AAV work breakdown structure. The library initially incorporated only proven low-risk technologies, but was expanded to high risk/high reward components based on the Innovation Team's research (Burrow et al., 2013). Component size, weight, and cost information was the basis for the Market Research Database (MRDB), which utilized the synthesis tool Framework for Assessing Cost and Technology (FACT) for evaluating ACV performance. With a library of components, a set of requirements, operational scenarios, and a performance synthesis model, the ACV design team was able to generate a large design trade space of potential configurations to satisfy capability concepts.

To evaluate the large trade space, individual studies were performed to first validate the design team's models and then to target specific design attributes. The Baseline Study was performed to validate the process models and design tools. The follow-on studies further explored technical viability and specific operational performance of HWS vs LWS ACVs. The four studies used multi-attribute utility theory to produce configuration Performance vs. Cost graphs.

The ACV design team claimed their use of diversity in design decisions was set-based; but the use of the SBD principles described in the section on the ACV was sparse. The only aspect of the SBD principles that occurred during the ACV design was the knowledge-sharing that occurred between the functional groups. This partial use of SBD has been identified by some researchers as aligning with effective trade space exploration (Ghosh & Seering, 2014; Schmid, 2015) and is a better description of the overall design approach used by the ACV design team. As the requirements group identified new or changing requirements from the USMC, they would update DOORS. A DOORS update changed the parameters of FACT, which then ultimately resulted in opening or eliminating some of the ACV configuration trade space. Additionally, as the Affordability Analysis team identified supply chain or logistic issues that resulted in the preference of one component over the other, the MRDB would be updated. Changed parameters in the MRDB resulted in configuration utility changes, which could impact final recommendation results. This knowledge-sharing represented separate groups of concurrently evaluating sub-systems (Principle 1). Outside of the SBD principles described previously, the ACV directorate introduced the topic of cost diversity in which the overarching SBD premise of the optimal solution residing within the feasible set was reinforced.

What Was Learned From ACV Design

Overall, the ACV design assessed HWS ACV feasibility and cost. The design team felt they achieved this goal by performing design in a way that produced presentable, understandable information to decision-makers. They felt the presentation of design information supported a high degree of confidence in cost and risk decisions. Interviews with ASN RDA and reviews of the literature confirmed what the ACV team believed, that leadership was very satisfied with the ACV design team results (ASN-RDA, 2016). In the end, the ACV team was able to address leadership "what if" questions succinctly and with the technical rigor to enable high confidence decisions. Additionally, the ACV concept design introduced and familiarized USN leadership with a design information presentation style founded on solution feasibility, viability, and diversity discovered through a SBD approach.

Ultimately, the USMC selected the LWS ACV configuration as the initial, affordable selection as part of an incremental acquisition strategy that could eventually include a HWS variant.

Small Surface Combatant Task Force (SSCTF)

On February 24, 2014, Secretary of Defense Chuck Hagel restructured the LCS program by directing the USN to provide alternate proposals to procure a more capable and lethal small surface combatant for the last 20 of 52 planned LCSs (O'Rourke, 2014). Originally, the LCS program was announced in 2001 as a variant of the Future Destroyer concept of operations amid the large decisions facing the USN after the 1997 Quadrennial Defense Review (O'Rourke, 2016b; Work, 2007).

In the spring and summer of 2014, the USN responded to SECDEF's LCS restructure direction by assembling a group of surface warfare, ship design, and industry experts: the Small Surface Combatant Task Force (SSCTF). The SSCTF received direction from ASN RDA and the CNO to (Garner et al., 2015):

- Establish the requirements for a small surface combatant
- Assess the requirements delta against the existing LCS (both sea frames)
- Translate the requirements delta into concept designs considering: existing ship, a modified existing ship, and new ship design options with schedule, cost, sensor systems, and lethality measures of performance.

Similar to the ACV concept design, one of the priorities for USN leadership was quickly coming to a well-informed decision to re-direct a program proceeding in the wrong direction. Fresh from the ACV concept design experience, a core group of NAVSEA 05D SDMs were available to advise the SSCTF on use of SBD in concept design. Their insights enabled the SSCTF to tailor their design approach to take advantage of the knowledge-sharing and concurrent work principles of SBD. The overall approach the SSCTF used to achieve their tasking: (1) capabilities were defined, (2) capabilities were translated into configurations of different ship systems to achieve required capability performance levels, and (3) synthesized ships were evaluated using utility theory for performance vs cost (Garner et al., 2015). During this effort, the SSCTF utilized the SBD principles described previously during synthesis and evaluation.

How SBD Was Used During SSCTF

One of the SBD principles used by the SSCTF design team was concurrent design of the Hull, Mechanical and Electrical (HM&E) and Combat Systems during synthesis. When designing and converging full ship designs, HM&E experts assumed the Space, Weight, Power and Cooling (SWAP-C) metrics for the combat system. HM&E designers utilized a large (low-risk) range for combat system SWAP-C architecture to more likely enable future ship convergence feasibility and therefore viability. Establishing these "placeholders" for combat system architecture allowed the combat warfare system experts to independently design their systems. As combat system design solutions matured, the matured combat system SWAP-C metrics were intersected with the HM&E assumptions to refine the solution space. Performing the HM&E and combat system work in parallel and then intersecting design efforts matches the first and second principles of SBD from the Set-Based Design section. The SSCTF claimed to follow the literary SBD principle of canvassing a large trade space, but just because a large trade space is generated at the onset of design doesn't make a design approach set-based.

What Was Learned From SSCTF Design

Three major points were learned from the SSCTF design effort. First, early stage ship SBD can be achieved by partitioning along HM&E and Combat Systems functional boundaries. The interfacial variables that exist between these two groups are physics-based variables which are easily quantified within existing design tools. Furthermore, USN ship design tools such as Advanced Surface Ship and Submarine Evaluation Tool (ASSET), Rapid Ship Design Environment (RSDE), and Leading Edge Architecture for Prototyping Systems (LEAPS) provide effective, rapid generation and comparison of ship designs independent of concurrently working in the HM&E or Combat System functional group. These tools easily intersect interfacial variables between the HM&E and Combat System functional groups. Second, USN leadership preferred the visual risk assessment and data presentation that accompanied the ASSET, RSDE, and LEAPs design products. Similar to the ACV design, USN leadership discussed their perceived confidence in decision-making based on the in-depth and easily decipherable data presented by SSCTF designers. Third, the USN ship design community has established a core group of designers that can responsively react to emergent ship design tasking and produce well received results in a rapid fashion. Overall, as the most recent SBD ship excursion, the SSCTF has helped validate the tools, processes, and metrics associated with a set-based surface ship design.

Summary of USN Cases of SBD

The four proposed benefits of SBD identified previously are assessed using available programmatic information for SSC, ACV, or SSCTF to determine whether evidence supports the claimed benefit. The proposed benefits of SBD are as follows:

- *Reduction of later stage rework when the cost of change is more expensive; therefore, less cost to design, build, and maintain the product*. This benefit did not specifically appear in literature or interviews for the SSC, ACV, or SSCTF, but can be inferred indirectly. Each of the USN SBD cases occurred early[3] during the ship product development life-cycle. Therefore, the overall acquisition cost performance of the ship program should be improved based on the SBD principle of reducing later more costly re-work. This can be assessed by reviewing the adherence of a program's actual acquisition cost to its original APB cost in a SAR. The ACV and modified-LCS have not proceeded past their MS B APB decision, so only the SSC can be assessed. Cost performance is captured in Figure 4 and shows that the SSC has the highest acquisition cost performance; achieving greater than 1.0 means that overall actual acquisition costs have decreased compared with the original APB estimates.

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[3] Even though the SSCTF design event occurred during mid-life of the LCS, it was evaluating ship design concepts from the beginning of the ship product development life-cycle.

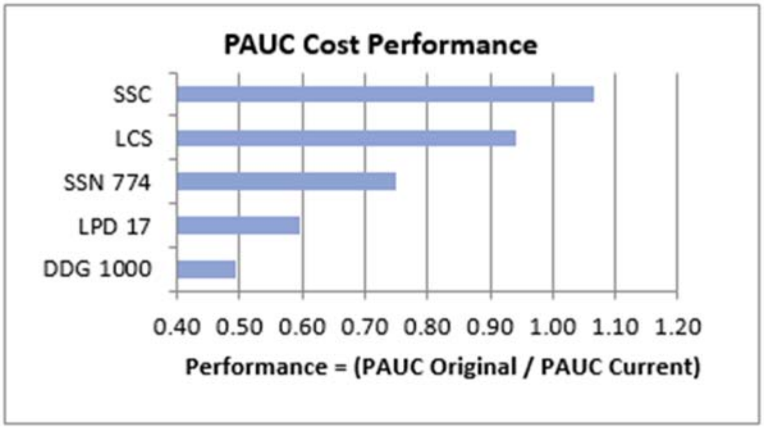

Figure 4. Per Unit Acquisition Cost Performance
(DAMIR, 2015)

- *Reduction of design cycle-time; therefore, less cost to design the product and more market share gained from entering an opportunity market sooner*. For each of the USN design cases studied, design cycle-time reduction was a goal of each design team. All three design teams reported producing results within a time-span previously not achievable. USN leadership confirmed the previously not achievable claim for each case. Therefore, this proposed benefit was realized by USN's use of SBD.
- *Better design knowledge capture; therefore, less costly to incorporate customer changes during design or to perform future similar product designs.* Knowledge capture was also a goal of each design case studied. In the SSC design, this attribute was realized by generating TSSs and the identification of negotiating relationships. The design team specifically stated that future modernization or recapitalization efforts for SSC would go smoother with the information gathered during SSC design. The likelihood of knowledge capture improving future design or cost performance for the ACV and SSCTF still remain to be seen. In ACV and SSCTF designs, the SBD discovery by elimination principle was not specifically adhered to throughout each design. Therefore, only time will tell if the USN will fully realize this proposed SBD benefit. This proposed benefit also hints at SBD being a more flexible design approach due to the ability to easily re-open parts of the design space that were previously excluded by a elimination/design space reduction decision. Although changing stakeholder or customer requirements was not highlighted by literature or reported as significant during interviews for each USN SBD case, this topic was discussed during a general interview with NSWC CD. NSWC CD reported conducting an internal study in which two different teams independently used SBD and PBD to design a surface combatant. The results of their study showed that the PBD team needed significantly more rework to accommodate requirements changes and the mid-life upgrade modernization (Gray, Rigterink, & McCauley, 2017). Therefore, this proposed benefit has been demonstrated in a structured ship design academic setting.
- *A better solution is found because of the methodic reduction of the design trade space; therefore, higher customer satisfaction*. To evaluate this benefit, the "customer" needs to be defined. For the three design cases, the customer could be acquisition leadership, or the USN sailor who will eventually operate

the warship product. Additionally, it is difficult to gauge the degree of satisfaction in both the acquisition leadership and USN sailor cases. As best determined from interviews with executives involved with the three cases studied, leadership was satisfied with the results of each design. They reported being able to better understand information presented during design update or final briefs based on the visual representation that accompanied the Monte Carlo simulations for ACV and SSCTF and the key variable reduction graph from SSC. Data presented in this manner was able to drive home the SBD principle point about designing through discovery by elimination.

Overall the case studies of USN SBD use showed that at least some of the SBD principles were adhered to. A major learning is that USN leadership has become more familiar and accustomed to the style and depth of early stage design information resulting from a set-based design approach. The proposed benefits of SBD were shown to have been realized in some capacity for each example. Last, SBD is acknowledged in USN ship design process instructions and SBD ship design tools continue to be developed in the USN.

New Path Forward Using SBD in Ship Design

The Secretary of the Navy has authored and issued SECNAV 5000.2E to depict how the USN will operate within the DAS/PPBE/JCIDS triad and describe the 2P/6G process for ship product development. The purpose of the 2P/6G process is to improve insight into ship development and execution of its acquisition (NAVSEA, 2010). For each gate, stakeholders and their priorities were identified through interviews with key stakeholders in the process, summarized in Table 1. Reflection on the priorities and outcomes of each gate suggest the following:

- SBD is not appropriate for Gate 1. The principles of SBD do not align with desired outcomes of the CBA and ICD because the CBA focuses on using existing ship designs and plans, and the conduct of an ICD doesn't require the sophistication or detail generated by SBD.
- The principles of SBD align with stakeholder priorities for Gate 2. The SBD principle of concurrent sub-subsystem evaluation aligns with the desire for trade studies.
- SBD is potentially the best method of providing what stakeholders want from Gate 3. Understanding the "drivers" of KPP/KSA cost requires that the ship designer understand "relationships" between systems that cause weight, which is what SBD does inherently.
- SBD may be amenable to activities during Gate 4 depending on the design progresses used in Gate 2 to Gate 3. Because the ship design is already partitioned and close to complete, utilizing SBD may or may not provide additional benefits over point-based or traditional ship design. The design method used during Gate 3 activities is likely to be the best to use during Gate 4.

Table 1. Gate 1–4 Stakeholder Priorities

Gate	What	Type of Design	Who	Priorities
1	ICD	Exploratory & Pre-AoA	N8	Understand intelligence & technology risks. Don't jump to conclusions.
2	AoA	AoA	CNO	Large span of AoA variants. AoA cost vs. capability trade-off information.
3	CDD	Pre-PD	CNO	Feasibility assessment of KPP/KSA performance values.
4	SDS	Preliminary	ASN RDA	Cost and feasibility of sub-system integration.

Gate 2 SBD Process Improvement: The Analysis of Feasibility

During interviews, discussions, and literature research, the AoA seemed to be the first large decision point and possibly the most influential in directing the course of a ship design. For ship design programs, the AoA occurs right at the time of the highest design influence on cost and capability. Almost every ship program researched had a foundational AoA that, at the very least, collected and described the basic need for the ship. Given the importance of the AoA in the ship design, it was surprising to discover that past USN ship AoAs have presented a limited and scripted selection of options that often fail to carry forward as the program progresses. This is because they are generally sparse point designs that offer neither a useful range of options nor useful insights to migrate toward a more optimal design. Given the amenability of SBD to Gate 2 stakeholder priorities and the historical poor performance of USN ship AoA's, the current ship AoA process was assessed for SBD process improvement opportunities.

Current ship design tools can support a different way to perform a ship AoA. This new approach uses RSDE's capability to communicate interfacial design variables to achieve the principles of SBD. This new method, termed the Analysis of Feasibility (AoF), improves the current AoA process by producing data that better aligns with DoD 5000.02 AoA guidance, eliminating the "middle point" pitfalls of past AoAs, and providing results in response surfaces instead of bar charts. Additionally, the AoF enables follow-on pre-preliminary design to continue in a set-based fashion. Most importantly, the AoF produces results in a fashion preferred by stakeholders to enable higher confidence decisions. Lastly, the AoF contributes to lower overall PAUC by preventing future re-work and shortening overall ship design cycle-time.

A process, similar to that used by the SSCTF, can be implemented using existing ship design tools and a set-based approach to improve Gate 2 activities. The SSCTF used two functional teams split between Combat Systems and HM&E to accomplish capability concept designs. The same AoF design team division could be used by a NAVSEA SCM, who is familiar with SBD, to generate a large span of variants to inform a ship AoF trade-off study.

Ship AoA's use the Design Reference Mission (DRM) from the ICD to determine required ship performance. For ships, the DRM determines the type and variety of Combat Systems, but not the sea frame that carries it. A simple analogy is to think of the Navy ship as a truck which carries the sensors and weapon systems to perform the DRM. The truck supplies the weapon systems with energy and physical support. Splitting a design team along the weapons system and truck functional boundaries would establish energy and physical support as interfacial variables; and thus, partition the design space into separate groups of experts (SBD Principle 1). By splitting into two functional teams, Ship and Combat System designers can independently and concurrently design sets of systems that meet the required performance of the DRM. Once design sets are complete, the two teams meet/communicate to share what range of energy and support each team needs from the other (SBD Principle 2). For example, determining how the truck is built determines how heavy or high the weapons system could be placed before the truck tips over or breaks. Likewise, the DRM would determine the size and type of weapons system needed.

In the USN ship design environment, ASSET has the capability to design the ship [truck] and place the weapons system. Bu, ASSET produces results for only one unique, individual ship and weapons system configuration at a time. Using ASSET with RSDE allows a range of ship design parameters and a range of weapon system locations and sizes to be analyzed concurrently. Figure 5 shows a visual description of how a range of combat system configurations could be varied while simultaneously varying ship parameters.

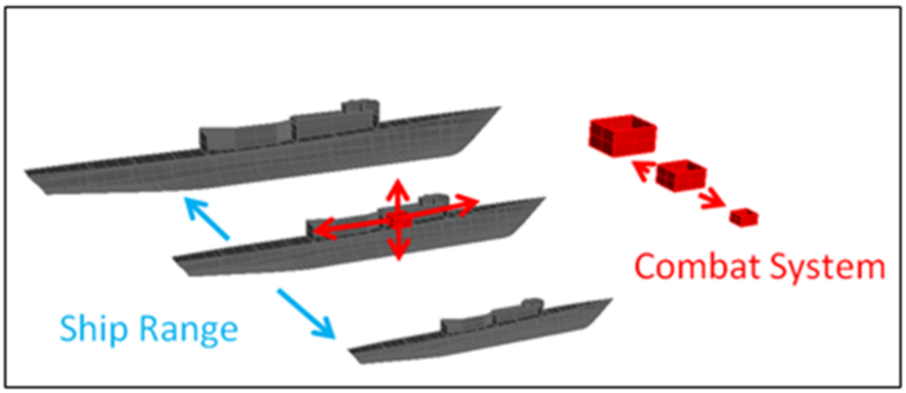

Figure 5. New AoF Variant Creation Process

Similarly, various different propulsion, power generation, and auxiliary cooling configurations are typically considered when performing early stage ship design when all available options should be included in the design trade space. Each set of ship parameters can be evaluated over the range of possible Combat Systems by simply utilizing RSDE to run multiple ASSET evaluations

Overall, conducting an AoF in a set-based manner produces a large number of variants that would fill in the middle points of a current state AoA. This larger data set should produce better capability and cost trade-off assessment for decision-makers using statistical tools like JMP. JMP can easily produce graphs and view charts that quickly show regions of the performance variables and how they change with variations in Ship or Combat System parameters. Most importantly, data presented in this manner is preferred by stakeholders over the classic cost and capability bar-charts. The concurrent evaluation of the trade space by the Ship and Combat System design experts should result in a faster design cycle-time. Also, the knowledge obtained by identifying the ranges of infeasibility for various Ship parameters and Combat System configurations is invaluable. This design knowledge is captured by the formal meeting/communicating process inherent to SBD and supports eliminating future more-costly re-work. Overall, using a set-based AoF approach in Gate 2 should support a lower ship program PAUC and faster acquisition.

Gate 3 SBD Process Improvement: Continue the AoF Analysis

Given the amenability of SBD to the stakeholder priorities of Gate 3, the AoF method provides an opportunity to improve Gate 3 ship design activities. With the priority of assessing the feasibility of KPPs/KSAs, the large trade space and design knowledge gained from Gate 2 AoF activities presents an excellent opportunity to support continued design feasibility assessments.

After a successful Gate 2 review board, the focus of the ship design team turns towards generating the CDD. Which ultimately means conducting enough design to assess if the performance levels required in the KPPs/KSAs can be achieved within cost and schedule targets. In the past, AoAs have produced preferred variants that do not represent the right combination of affordable capability; thus, ship program sponsors have had to fund re-design efforts on AoA resultant variants. These redesign efforts present an improvement opportunity for Gate 3. Continuing the AoF design method can reduce or prevent the re-design effort experienced in past Pre-PD and PD designs.

The AoF design method reduces or prevents AoA variant re-design by keeping the design trade space open across the Gate 2 review board. In the past, AoAs were contained design events that only produced a written report to make a decision. AoA ASSET ship models were retained by NAVSEA 05D, but rarely re-used because exact AoA variants tended to not exactly align with what the ship program manager desired for the CDD.

To continue the AoF in Gate 3, the SDM would start by re-evaluating the design team functional partition to identify sub-regions of expertise for further concurrent evaluation. For example, in the Gate 2 AoF, the propulsion system was only at the “type” level. A specific Propulsion design team could be created during Gate 3 with identified interfacial design variables of space, thrust, and weight with the Ship design team. This would support evaluating “options” of different propulsion methods. Once a span of propulsion options has been studied, the propulsion team would communicate the exact space, thrust, and weight of their preferred propulsion choice to the Ship team. This would most likely eliminate some of the propulsion options from consideration and thus refine the performance of the overall ship. The ship design tools ASSET and RSDE could be used to perform this type of sub-group study. Figure 6 highlights the Propulsion design team example communicating across the identified interfacial variables.

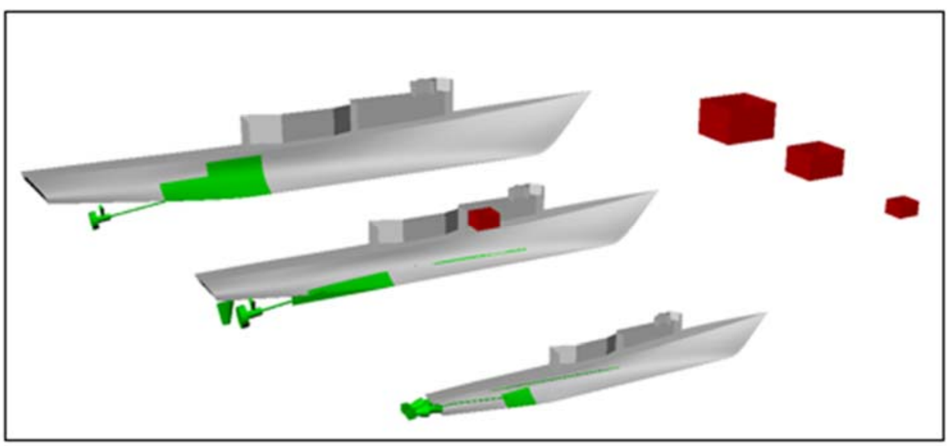

Figure 6. Propulsion Option Exploration

Overall, continuing the AoF approach in Gate 3 provides the SDM with the opportunity to flexibly adjust the design team in areas of the design that may need more specific evaluation to provide a feasible assessment of required KPP/KSA performance. Also, it limits the iterations of re-design performed in the past by keeping the real design trade space open and using SBD to reduce or eliminate dominated sub-system options. Thus, the AoF represents a potentially better way to proceed through Gate 3 activities.

Conclusion

This discussion illustrated how the stakeholder priorities of Gates 1–4 can be addressed by SBD. Gates 2 and 3 were identified as the most likely candidates for SBD process improvement. The Analysis of Feasibility, using SBD principles and existing modern ship design tools, was introduced as a way to improve overall ship program PAUC and design cycle-time by segmenting the to-be-designed ship initially into Ship and Combat System functional design teams. The AoF method illustrates the capability to keep the ship design space open across the Gate 2/3 boundary. In sum, the AoF method uses existing ship design tools and SBD principles to deliver Gate 2 and 3 stakeholder priorities in a preferred fashion.

Conclusion

The proposed process improvement initiatives described in this work are within the capability of the current USN ship design and acquisition workforce. Future work might entail the development of new written policy and guidance at an institutional level. Furthermore, the USN should continue its investment in ship design and process tools that align with the principles of SBD. The proposed benefits of SBD, as applied to USN ship design, are potentially significant. In the face of near- to mid-term ship acquisition challenges, aligning the amenable aspects of the 2P/6G USN ship design process with SBD is one of the more promising opportunities to realize ship design and acquisition improvement.

References

ASN-RDA. (2016, January 22). Executive.

Bernstein, J. I. (1998). *Design methods in the aerospace industry: Looking for evidence of set-based practices* (Master's thesis). Cambridge, MA: Massachusetts Institute of Technology.

Buckley, M., & Stammnitz, V. (2004). Decision oriented systems engineering (DOSE)—A Structured, systematic approach to function allocation. *14th Annual International Symposium for INCOSE.*

Burrow, J., Doerry, N., Earnesty, M., Was, J., Myers, J., Banko, J., . . . Tafolla, T. (2013). Concept exploration of the Amphibious Combat Vehicle. *SNAME Maritime Convention*. Houston, TX. Retrieved from http://www.doerry.org/norbert/papers/20140726ConceptExplorationoftheAmphibiousCombatVehicle.pdf

CDI Marine, B. L. (2009). *Ship-to-shore connector implementation of set based design* (Working Paper 765.002.023-1).

Chapman, W., Bahill, T., & Wymore, A. (1992). *Engineering model and design*. Boca Raton, FL: CRC Press.

DAMIR. (2015, December 15). *Defense Acquisition Management and Information Retrieval.* Retrieved from Selected Acquisition Reports (various programs): http://www.acq.osd.mil/damir/

Doerry, N. (2010). Transitioning technology to naval ships. Washington, DC: NAVSEA 05T.

Evans, J. (1959). Basic design concepts. *American Society of Naval Engineers Journal, 71*(4), 672–678.

Fireman, H., Nutting, M., Rivers, T., & Carlile, G. (1998). LPD 17 on the shipbuilding frontier: Integrated product and process development. In *Proceedings of the Association of Scientists and Engineers 35th Annual Technical Symposium.*

Frye, M. (2010). *Applying set based methodology in submarine concept design* (Master's thesis). Cambridge, MA: Massachusetts Institute of Technology.

Garner, M., Doerry, N., MacKenna, A., Pearce, F., Bassler, C., Hannapel, S., & McCauley, P. (2015). *Concept exploration methods for the Small Surface Combatant.* Retrieved from http://www.doerry.org/norbert/papers/20150717ssc-ce.pdf.

Ghosh, S., & Seering, W. (2014). Set-based thinking in the engineering design community and beyond. In *Proceedings of the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* (pp. DETC2014–35597). Buffalo, NY.

Gray, A. (2011). *Enhancement of set-based design practices via introduction of uncertainty the use of interval type-2 modeling and general type-2 fuzzy logic agent based methods* (Doctoral dissertation). Ann Arbor, MI: University of Michigan.

Gray, A., Rigterink, D., & McCauley, P. (2017). *Point-based versus set-based design method for robust ship design.* Carderock, MD: Naval Surface Warfare Center Carderock Division.

Kassel, B., Cooper, S., & Mackenna, A. (2010). Rebuilding the NAVSEA early stage ship design environment. *American Society of Naval Engineers,* 1–12.

Keane, R., Firemann, H., Hough, J., Helgerson, D., & Whitcomb, C. (2009). Ready to design a naval ship? Prove it! *Journal of Ship Production*, 45–58.

Keane, R., McIntire, J., Fireman, H., & Maher, D. (2009). The LPD 17 ship design: Leading a sea change toward collaborative product development. *Naval Engineers Journal, 121*(2), 15–61.

Liker, J., Sobek, D., Ward, A., & Cristiano, J. (1996). Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering. *IEEE Transactions on Engineering Management, 43*(2), 165–178.

McKenney, T., & Singer, D. (2014, July). Set-based design: A concurrent engineering approach with particular application to complex marine products. *Marine Technology*, 51–55.

Mebane, W., Carlson, C., Dowd, C., Singer, D., & Buckley, M. (2011). Set-based design and the ship to shore connector. ASNE Day (February 9–10, 2011). Arlington, VA.

NAVSEA. (2010). *Acquisition strategy guide*. Washington, DC: Naval Sea Systems Command.

NAVSEA. (2012). *Ship design manager's and ship integration manager's manual.* Washington, DC: Naval Sea Systems Command.

O'Rourke, R. (2014). Na*vy Littoral Combat Ship (LCS) program: Background and issues for Congress*. Washington, DC: Congressional Research Service.

O'Rourke, R. (2016a). *Marine Corps Amphibious Combat Vehicle (ACV) and Marine Personnel Carrier (MPC): Background and issues for Congress*. Washington, DC: Congressional Research Service.

O'Rourke, R. (2016b). *Navy Littoral Combat Ship (LCS)/Frigate program: Background and issues for Congress*. Washington, DC: Congressional Research Service.

Raudberget, D. (2010). Practical applications of set-based concurrent engineering in industry. *Journal of Mechanical Engineering, 56*(11), 685–695.

Rhodes, D., & Ross, A. (2016, March 4). *Engineered resilient systems—Systems engineering: Knowledge capture and transfer*. Retrieved from Stevens Institute of Technology website: http://www.sercuarc.org/wp-content/uploads/2014/05/SERC-2014-TR045-1EngineeredResilientSystemsRT103-0829FINALmm.pdf

Schmid, R. (2015). *Performance measuring of set-based concurrent engineering in comparison to point-based concurrent engineering using system dynamics* (Master's thesis). Munich, Germany: Technical University of Munich.

Singer, D., Doerry, N., & Buckley, M. (2009). What is set-based design? *Naval Engineers Journal, 121*(4), 31–43.

Sobek, D., Ward, A., & Liker, J. (1999). Toyota's principles of set-based concurrent engineering. *Sloan Management Review, 40*(2), 67–83.

Sullivan, P. E. (2008). *Ship design and analysis tool goals* (Ref: COMNAVSEA memo 9000 Ser 05D/047).

Ward, A. C. (1989). *A theory of quantitative inference for artifact sets, applied to a mechanical design compiler* (Doctoral dissertation). Cambridge, MA: Massachusetts Institute of Technology.

Ward, A., Liker, J., Cristiano, J., & Sobek, D. (1995, Spring). The second Toyota paradox: How delaying decisions can make better cars faster. *Sloan Management Review, 36*(3), 43–61.

Work, R. (2007). *Know when to hold 'em, know when to fold 'em: A new transformation plan for the Navy's surface battle line*. Washington, DC: Center for Strategic and Budgetary Assessments.

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